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MODEL-BASED SIMULATION, ANALYSIS, AND PROTOTYPING FOR FUTURE LIQUID AIR ENERGY STORAGE SYSTEMS

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THESIS

MODEL-BASED SIMULATION, ANALYSIS, AND PROTOTYPING FOR FUTURE LIQUID AIR ENERGY STORAGE SYSTEMS

by

Nicholas A. Bailey

December 2019

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Islanded, renewably powered microgrids require energy storage or emergency generation to overcome intermittency. Batteries and fossil fuel generators have traditionally filled these roles. However, liquid air energy storage (LAES) is a promising alternative. Using power in excess of immediate demand, a LAES system can liquefy and cryogenically store ambient air. When renewable generation abates, the liquid air can be heated and expanded to provide power to the microgrid. Using a modeling and simulation approach, the requirements for a Linde-Hampson based LAES system satisfied a building scale (5 kW) demand for five hours. Functional requirements for the system are established and most significant factors are examined. Compressor pressure and flow are identified as the most important towards liquid yield, and components to realize a complete system are selected. Next, a dual-Stirling engine-based LAES system focusing on the energy generation subsystem is explored. Experimental data were gathered from a prototype that was built and compared against an ideal Stirling cycle. Energy efficiency was calculated, and improvements were suggested. Both LAES systems presented are coupled with Girouard, Pollman, and Hernandez's LAES research into a supply-based Linde-Hampson system and the liquid generation subsystem of a dual-Stirling engine prototype to form two complete LAES systems.

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MODEL-BASED SIMULATION, ANALYSIS, AND PROTOTYPING FOR FUTURE LIQUID AIR ENERGY STORAGE SYSTEMS

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Submitted in partial fulfillment of the
requirements for the degree of

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December 2019

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ABSTRACT

Islanded, renewably powered microgrids require energy storage or emergency generation to overcome intermittency. Batteries and fossil fuel generators have traditionally filled these roles. However, liquid air energy storage (LAES) is a promising alternative. Using power in excess of immediate demand, a LAES system can liquefy and cryogenically store ambient air. When renewable generation abates, the liquid air can be heated and expanded to provide power to the microgrid. Using a modeling and simulation approach, the requirements for a Linde-Hampson based LAES system satisfied a building scale (5 kW) demand for five hours. Functional requirements for the system are established and most significant factors are examined. Compressor pressure and flow are identified as the most important towards liquid yield, and components to realize a complete system are selected. Next, a dual-Stirling engine-based LAES system focusing on the energy generation subsystem is explored. Experimental data were gathered from a prototype that was built and compared against an ideal Stirling cycle. Energy efficiency was calculated, and improvements were suggested. Both LAES systems presented are coupled with Girouard, Pollman, and Hernandez's LAES research into a supply-based Linde-Hampson system and the liquid generation subsystem of a dual-Stirling engine prototype to form two complete LAES systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CAES	Compressed Air Energy Storage
DOD	Department of Defense
JT	Joule-Thompson
LAES	Liquid Air Energy Storage
MORS	Military Operations Research Society
PV	Pressure-Volume
TES	Thermal Energy Storage
USMC	United States Marine Corps

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EXECUTIVE SUMMARY

Energy production using renewable sources face some barriers to widespread adoption and a total shift away from fossil fuel-based traditional generation plants. One of the largest obstacles is the issue of resiliency with renewable sources (Sovacool 2009). When the sun sets on solar power or the wind stops blowing a wind turbine, generation also halts. Islanded, renewably powered microgrids require energy storage or emergency generation to overcome intermittency and provide grid resiliency. Batteries, compressed air energy storage, and pumped hydroelectric power are viable energy storage options, though they create harmful byproducts or are geographically unfeasible in some areas (Luo et al. 2015). Liquid air energy storage (LAES) is a promising alternative that eliminates the listed system downsides. Using power in excess of immediate demand, a LAES system can liquefy and cryogenically store ambient air. When renewable generation sources abate, the stored liquid air can be heated and expanded to provide power to the microgrid.

The first LAES system explored in the present work is a Linde-Hampson cycle system. Air is liquefied using the Joule-Thompson effect and stored cryogenically within a storage dewar. When needed the liquid air is heated to a phase change with the resulting vapor used to drive an expansion turbine generator (Lim, Al-Atabi, and Williams 2016). The presented conference paper investigates this system using a modeling and simulation approach at building-scale size of five kilowatts. This work builds upon previous theoretical LAES system research by Howe (Howe 2018) and uses the validated Aspen HYSYS model created by Willis in order to create functional requirements and select components for the system (Willis 2018). The model shows that for peak system efficiency, air compressor pressure and flow rate are the most significant factors to maximize liquid yield within the system. Follow-on research includes further optimization as well as system realization to compare performance in real life versus simulation.

Next, a dual-Stirling engine based LAES system is examined, focusing specifically on the energy recovery and generation subsystem. Using a Stirling engine, energy is recovered from liquid air using only temperature differences between the boiling liquid air and outside environment. Experimental data was gathered from a prototype that was built

and compared against an ideal Stirling cycle. Data collected includes voltage and current produced, liquid air mass consumed, and Stirling engine heat sink temperature. Experiments were conducted over a varying resistive load and statically analyzed. Results from these experiments were compared to the ideal Stirling cycle efficiency and coefficient of performance and improvements were recommended to increase measured performance. Both LAES systems are presented in conjunction with Girouard, Pollman, and Hernandez's ongoing research into the viability of LAES within the military (Girouard, Pollman, and Hernandez 2019).

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I. INTRODUCTION

A. MOTIVATION

Energy usage within the Department of Defense (DOD) varies greatly from other large energy consumers. The extent and ways in which energy is used is different within the five services but also within each service, and the end users comprise both land-based installations as well as forward-deployed, mobile forces. Providing this power within an ever-changing production landscape is a priority for the DOD (Willis 2018).

In 2010, the Navy outlined a new shore energy management policy to set long-term energy goals and manage installation energy consumption better (United States Navy 2010). OPNAVINST 4100.5E establishes specific shore energy goals to be met by 2020 (Office of the Chief of Naval Operations 2012). A selection of the goals mandates a 50% reduction in total shore energy consumption and 50% of total shore energy production from renewable sources (Office of the Chief of Naval Operations 2012). Meeting these energy goals would reduce the total cost of shore energy production, currently calculated to be 28% of the total installation budget (United States Navy 2018). More reliance on renewable sources will also reduce the Navy's reliance on legacy fossil fuel generation technologies being phased out within the changing energy production landscape.

The United States Maine Corps (USMC) has also realized that its dependence on fossil fuel-based energy production leaves the service vulnerable as an expeditionary force (Marine Corps Expeditionary Energy Office 2011). The service's logistics of hauling fuel to create energy also leads to further vulnerabilities for exploitation (Pollman 2013). By increasing the use of renewable energy sources, the USMC can travel with fewer supplies, making their fighting force faster, more austere, and ultimately more lethal (Marine Corps Expeditionary Energy Office 2011). United States military services recognize that their reliance on fossil fuel-based energy production should diminish and give way to renewable sources. Thus, choosing the best type of renewable energy generation is a critical decision to get correct.

B. PROBLEM OVERVIEW

Islanded, renewable energy production architectures, by their nature, suffer generation intermittency. Current, more traditional, architectures are resilient systems compared to distributed renewable source grids, meeting near-constant energy demand requirements. The increased resiliency of traditional centralized energy production, such as fossil fuel production plants, comes at great costs due to release of undesirable emitted byproducts in greenhouse gases and high fuel prices. To replace the current systems in a viable way, intermittency must be eliminated with renewable energy sources.

C. ENERGY STORAGE TECHNOLOGIES

1. Overview

Many different renewable sources can solve these intermittency issues through various methods. Thermal energy storage (TES) and, more specifically, liquid air energy storage (LAES) is one such technology that may be able to overcome intermittency and increase resiliency. Figure 1 shows the specific power and specific energy of various energy storage technologies. High specific power is required when strong, immediate demands are placed on a grid. whereas high specific energy describes how much energy can be extracted from a known mass. Applications vary, though generally, a combination of high specific power and energy is desired. TES technologies are on the same order of magnitude for specific energy as lithium ion batteries, a front-running and rapidly expanding energy storage method. TES generation has low specific power compared to other alternatives, but the weakness can be overcome.

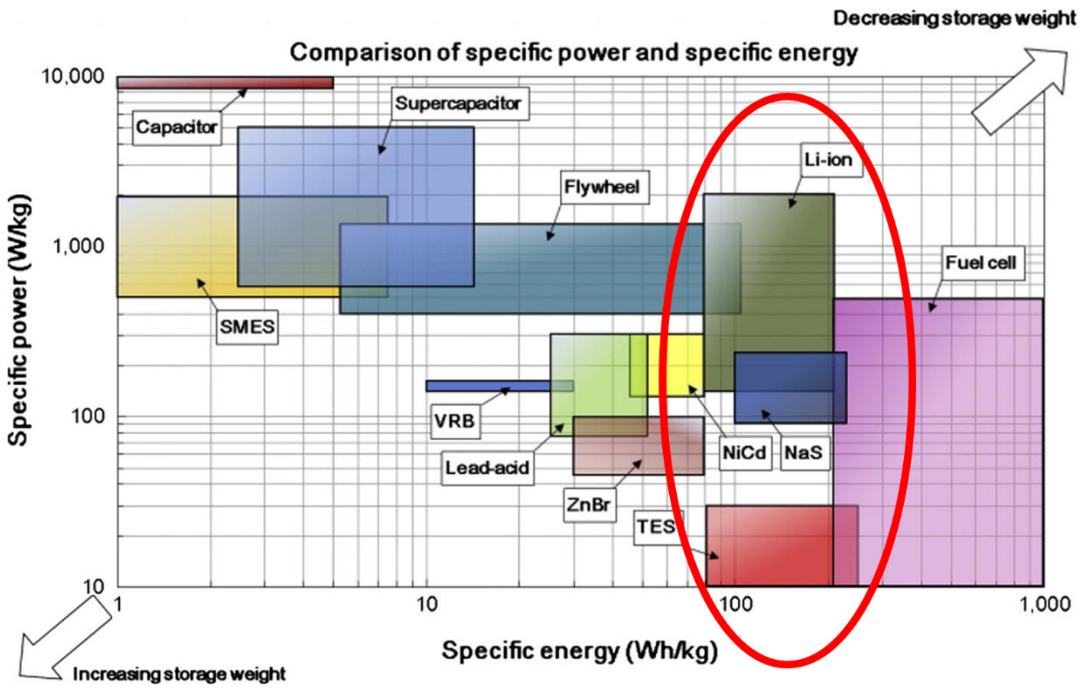

Figure 1. Comparison of specific power and specific energy of various storage technologies. Source: Luo et al. (2015).

TES, specifically LAES, has an advantage over other technologies when comparing discharge rates. Figure 2 shows that cryogenic energy storage provides higher rated power for a longer duration of time than lithium ion batteries and is more desirable for higher-level transmission and distribution systems and is even suitable for bulk power management. For power full-scale installations, cryogenic energy storage is a well suited technology to provide power transmission and grid support over presently used alternatives.

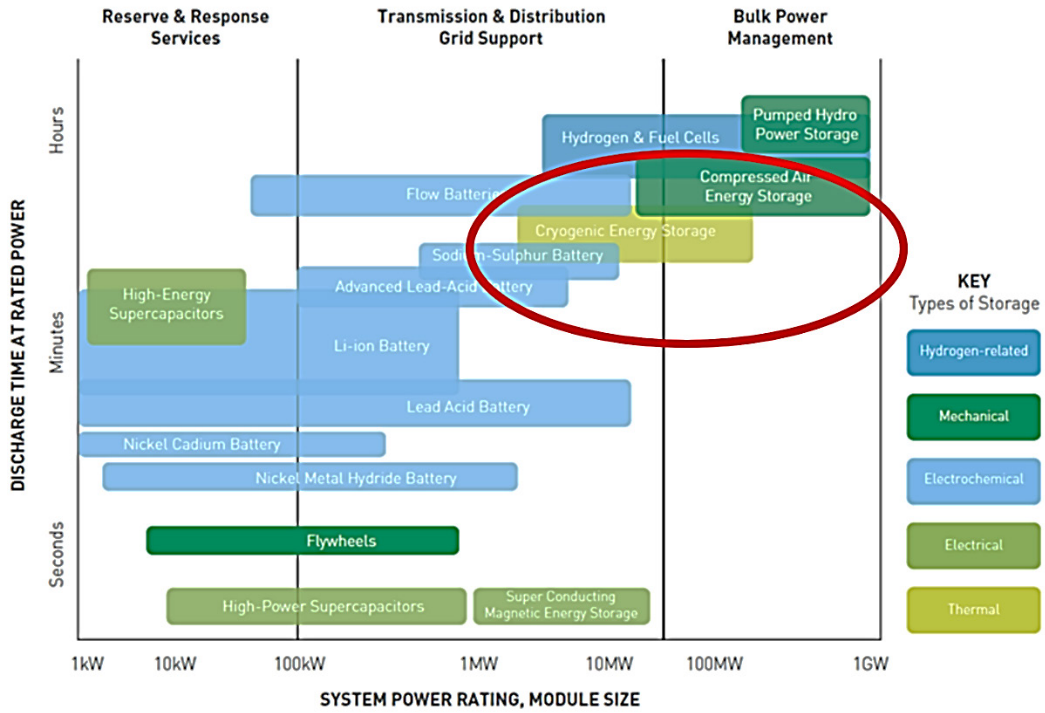

Figure 2. Discharge rate and power rating of selected energy generation technologies. Adapted from Hong and Radcliffe (2016).

2. Liquid Air Energy Storage

A LAES system is comprised of two independent subsystems: a compression subsystem and an expansion subsystem. These subsystems never operate simultaneously. The subsystems share a resource, liquefied air, and can use the waste heat or cooling to improve heat transfer between functions. Two different methods of liquid air generation are discussed in this thesis: Linde-Hampson cycle LAES and Stirling Cycle LAES.

a. Linde-Hampson Cycle LAES

Linde-Hampson cycle LAES takes advantage of the Joule-Thompson effect to generate the liquefied air for energy generation. Using compressed high-pressure vapor air expanded isentropically, the air rapidly cools and after cycling to cryogenic temperatures, liquefies. When needed, the liquefied air is expanded and used to do work, normally through a turbine. Chapter II discusses a Linde-Hampson cycle LAES system in detail.

b. Stirling Cycle LAES

An alternative LAES system involves two Stirling engines to create liquid air and recovery energy from that stored liquid air. By putting work into a standard Stirling cycle, cryogenic temperatures can be achieved and used to create liquid air. That air is stored until needed and then used to create a temperature difference with a second Stirling engine. This secondary Stirling engine recovers energy as the liquid air boils away. Chapter III introduces and explains this LAES system in detail.

D. RESEARCH QUESTIONS

1. Does the implementation of emerging renewable energy technologies for the U.S. Navy and USMC serve as viable options for their shore energy plants and expeditionary forces?

2. Do LAES technologies, specifically Linde-Hampton LAES and Stirling Cycle LAES systems, provide demonstrably resilient energy solutions that also eliminate intermittency?

E. THESIS OVERVIEW

This thesis follows the manuscript formatting option and presents the core information using two submitted conference papers. These two submitted papers present different approaches to a LAES concept, while also representing different levels of design maturity. The result is that these two design options fall within different phases of the systems engineering life cycle process.

1. Systems Engineering Relevance

To aid in the development of the overall systems engineering approach, the systems engineer Vee model is used to help qualify what stage in the development process these two presented systems are in. The Vee model provides illustrations of useful life cycle stages within the developmental process and presents a sequential methodology for various key areas within the systems engineering focus (INCOSE 2015). The presented conference papers in Chapters II and III are classified in different life cycle stages within the Vee model. Paper I presents a model based Linde-Hampson cycle LAES system from a demand perspective. This paper follows previous thesis work verifying the theoretical results of such a system and the creation of a verified model that was used within Paper I. Lastly, the paper offers sample component selections following the specifications outputted from the modeling effort. Essentially, the Linde-Hampson cycle LAES system described in Paper I shows the system moving from conceptual to preliminary design, or more specifically from the lower level systems element development to the realization states of the Vee model, as shown in Figure 3.

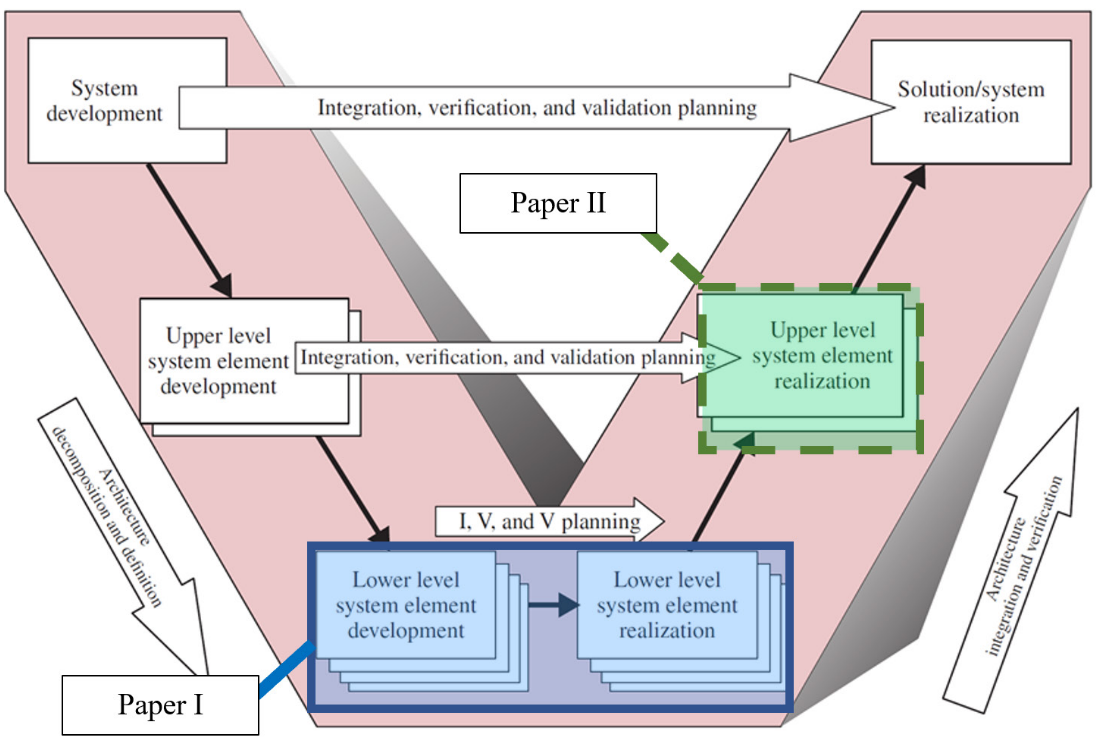

Figure 3. Systems engineering Vee model and Paper I and II classification within. Adapted from INCOSE (2015).

Paper II in Chapter III presents an LAES technology that is beyond the conceptual design phase and is clearly moved to preliminary design and realization of a prototype of the specific system. This paper presents the energy recovery from liquefied air using a Stirling engine. It is presented within a larger dual-Stirling engine LAES system, whereas a Stirling cryocooler liquefies air for storage and the recovery Stirling engine produces energy using the temperature difference between the ambient and cryogenic temperatures. Paper II presents ideal work calculations as well as data collected from a prototype of the system. Paper II is classified within the upper level system element realization stage of the Vee model. Though the full system is realized within Paper II, it is merely a prototype, not a polished and optimized system developed for a purpose.

2. Thesis Structure

The previous sections introduced the motivation, selected energy technology with rationale, and a brief introduction to LAES systems. It also introduces the two different type of LAES technologies to be presented in subsequent chapters. Chapter I also briefly describes the systems engineering process and where this work fits within the Vee model. Chapters II and II present the exact copies of conference papers submitted. Chapter II was submitted and presented at the 87th Symposium for the Military Operations Research Society (MORS). As of the date of this writing, Chapter III has been submitted to the American Society of Mechanical Engineers (ASME) Power 2020 conference. The subjects of these papers were introduced previously. Finally, Chapter IV summarizes the results and describes follow-on research opportunities within the subjects presented.

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II. PAPER I: “Modeling and Simulation Approach to Support Component Selection for Demand-Based Building-Scale LAES System”

This chapter has been prepared in conjunction with a presentation given at the 87th Symposium of the Military Operations Research Society (MORS) by the authors Nicholas A. Bailey, Anthony G. Pollman, and Eugene Paulo. Minor edits have been made to enhance readability and adapt publication formatting.

A. ABSTRACT

Islanded, renewably powered microgrids require energy storage or emergency generation to overcome intermittency. Batteries and fossil fuel generators have traditionally filled these roles. However, liquid air energy storage (LAES) is a promising alternative. Using power in excess of immediate demand, a LAES system can liquefy and cryogenically store ambient air. When renewable generation abates, the liquid air can be expanded through a turbine to provide power to the microgrid. Using a modeling and simulation approach, this paper explores the requirements for a Linde-Hampson based LAES system to satisfy a building scale (5 kW) demand for five hours. Analysis is used to assess round trip efficiencies, as a function of pressure ratios, number of compression or expansion stages, and other physical component decisions or configurations. Finally, the initial design and preliminary commercial component selection of a LAES system based on a demand requirement is presented. This effort, coupled with Girouard, Pollman, and Hernandez’s supply side analysis, effectively maps the extremes of the feasibility region. Future work will include construction at the Naval Postgraduate School’s microgrid test facility.

B. INTRODUCTION

The cost to produce and maintain energy on Navy shore installations consumes the highest percentage of the overall installation budget at 28%. These resources could instead be allocated toward fleet and training support (United States Navy 2018). The Navy (2018) established a new shore energy management approach in 2010 to better use these resources and manage longer-term energy goals.

These target goals are laid out in OPNAVINST 4100.5E. The instruction establishes the goals of reducing ashore energy consumption by 50% and increasing ashore energy production from alternative sources by 50%; both should be accomplished before 2020 (Office of the Chief of Naval Operations 2012). It also directs the Navy to integrate mission compatible and cost-effective renewable energy sources into the current energy architecture.

Other service branches are also investing into researching renewable energy systems for their own uses. The United States Maine Corps (USMC) has realized its dependence on fossil fuel-based energy production leaves the service vulnerable as an expeditionary force (Marine Corps Expeditionary Energy Office 2011). This dependence also creates vulnerabilities due to the logistics of hauling fuel to create energy (Pollman 2013). The USMC aims to increase the use of renewable energy sources as a means to travel with fewer supplies making their fighting force faster, more austere, and ultimately more lethal (Marine Corps Expeditionary Energy Office 2011).

The shift of energy production from current, more traditional, centralized methods to distributed renewable sources has some inherent problems that the current architecture does not suffer. Current architectures are resilient systems compared to distributed renewable source grids, meaning that they meet near-constant demand requirements. The increased resiliency of traditional centralized energy production comes at great costs due to release of undesirable emitted byproducts as well as at great expense because of the price of fuel. To replace the current systems viably, intermittency must be eliminated with renewable energy sources.

C. LAES BACKGROUND

Microgrids provide resiliency to consumers when acting in an islanded mode by using local renewable power sources. Local renewable power sources such as wind or photovoltaic production suffer from the problem of intermittency, thus requiring some form of energy storage to achieve reliability and effectiveness. There are multiple ways to achieve resiliency within a production plant. Some forms of renewable energy are already resilient while others must by implemented with other technologies. A system of systems approach to resiliency combines renewable energy sources with battery storage. This potential solution charges the batteries during high production times and then uses the stored charge when renewable sources abate. While both these technologies are mature, battery production causes many of the same undesirable emissions and byproducts that current production methods also produce. Batteries are also expensive to buy, use exotic materials, are hard to dispose of, and do not maintain their charge capacity for a long length of time.

Pumped hydroelectric power is another potential solution to enable resiliency. These types of systems have almost no intermittency problems. As long as water keeps flowing, the system makes energy. Hydroelectric power is geographically dependent on being close to a body of water that can be the catalyst for production. Elevation change is required for these systems whether manmade or natural. Manmade potential can either be from damming the water source or pumping it to a higher elevation (Luo et al. 2015). Most Department of Defense (DOD) military installations do not reside in the required geographic locations to make hydroelectric power viable and terraforming to create viability is cost prohibitive.

Another potential alternative is compressed air energy storage (CAES). The CAES systems work in tandem with other renewable sources, such as solar and wind generation sources. While energy is being produced with the renewable sources, any energy in excess of immediate demand is used to compress and store ambient air in the CAES system. When needed, the compressed air is re-expanded and used to drive a turbine generator. Small-scale CAES systems are viable, but when increasing scale, the compressed air storage location vessels are more difficult to find or build. There are, however, more viable CAES storage locations compared to pumped hydroelectric locations (Luo et al. 2015). CAES systems are often inefficient due to much of the compressor work going towards heating the newly compressed air (Luo et al. 2015). These systems are less efficient than battery electric storage, but do not have the same byproducts and costs associated. Benefits further include low maintenance and sustainment costs as well as unlimited cycles; however, these systems are a significant investment to set up initially.

Lastly, LAES systems combine the best attributes of CAES and battery electric storage. Much like the CAES system, excess energy from external sources is used to drive a compressor while generation is high. Instead of simply compressing and storing the air, it is instead liquefied and cryogenically stored. LAES is more energy dense than CAES systems and does not produce the undesirable byproducts of battery electric storage (Luo et al. 2015).

A LAES system is comprised of two independent subsystems; a compression subsystem, and an expansion subsystem. These subsystems never operate simultaneously. The subsystems share a resource, liquefied air, and can use the waste heat or cooling to improve heat transfer between functions. Figure 4 functionally decomposes a general LAES cycle.

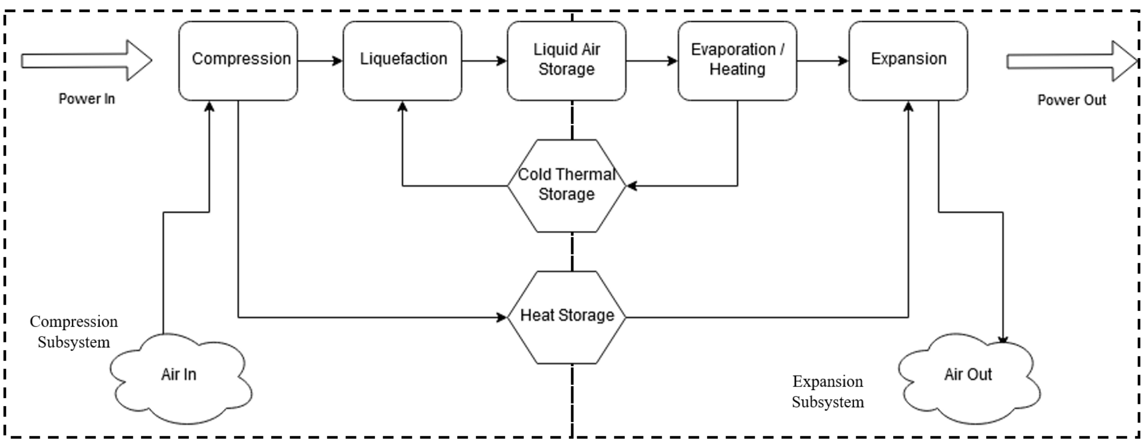

Figure 4. Functional diagram of LAES system. Adapted from Sciacovelli, Vecchi, and Ding (2017).

The compression subsystem takes ambient air and compresses it followed by a rapid expansion until a gas-to-liquid phase change occurs. After the air liquefies, it is stored cryogenically where it remains until utilized by the expansion subsystem. This liquefaction function is performed using excess generated power from renewable sources that would normally be wasted.

When needed, the expansion subsystem takes the stored liquid air and expands it back into vapor form. The work of this expansion is used to drive a turbine generator, creating power for the connected grid. The complete system will never simultaneously create liquid air and use it to generate energy at the same time.

The components of a generalized Linde-Hampson LAES system are shown in Figure 5. The compression function is performed by an air compressor. This component takes ambient air and compresses it to a specified pressure. This compressed air vapor is directed through the regenerative heat exchanger and Joule-Thompson (JT) valve to liquefy the air. The regenerative heat exchanger cools the compressed air back to the ambient air temperature. The JT valve isentropically expands the compressed air creating both condensed liquid air and a two-phase air mixture. The liquid air is stored in the dewar until needed for use in the expansion subsystem, while the two-phase air mixture is used to cool the compressed air in the regenerative heat exchanger and then recycled through the compressor. To start the evaporation/heating function, a pump moves the liquid air from the dewar to the evaporative heat exchanger. The evaporative heat exchanger warms the liquid air and causes a phase change back to a high-pressure vapor. The reheated and expanded high-pressure vapor is passed through the turbine, creating rotational shaft motion. This rotating shaft drives a generator, creating the electrical energy for the microgrid.

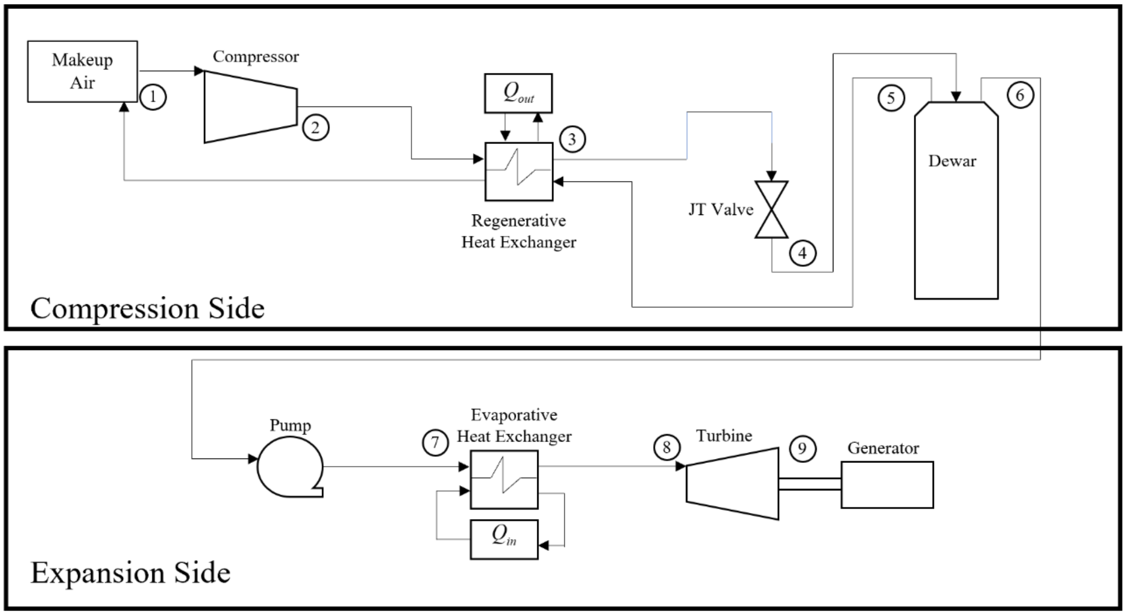

Figure 5. Component diagram of LAES system. Adapted from Girouard, Pollman, and Hernandez (2019).

Efficiencies of an ideal LAES system vary based upon operating conditions. Howe (2018) used fluid tables for ideal oxygen and nitrogen gasses to calculate theoretical system efficiency and determine ideal operating conditions for a LAES system. He found that generally, as the compression ratio increases, the efficiency of the system increases. Overall system efficiency and liquid air yield have different optimum operating conditions. Optimal liquid yield occurs when the compressor pressurizes the ambient air from 20–50 MPa (Howe, Pollman, and Gannon 2018). Maximum system efficiencies can exceed 50%, however optimal liquid yield reduces this efficiency to approximately 5% (Howe 2018).

Further building upon Howe's theoretical calculations, Willis (2018) built upon an ideal Linde-Hampson cycle LAES system modeled within the Aspen HYSYS simulation program (Joshi, Patel 2015). Aspen HYSYS is a leading industrial energy simulation software used within the energy community. Willis's model allows for operating conditions of the system to be varied and rapid iteration and simulation to occur. Using the operating conditions from Howe's theoretical approach, the model produced conditions and efficiencies within 5% of Howe's calculations, validating the model for further use (Willis 2018).

D. DEMAND-BASED ASPEN HYSYS MODEL

The present work was modeled and analyzed from a demand-based perspective. A building-size scale was selected; five kilowatts of power is needed to be produced and sustained by the system. Next, a time frame was adopted. This building scale LAES system would primarily function as a backup system for when power from the area grid is disrupted. It would need to operate for five hours, nominally enough time for power from the area grid or alternative energy generation sources to be restored. The total energy output of this system is therefore 25 kWh. Figure 6 presents the model used within the simulation software.

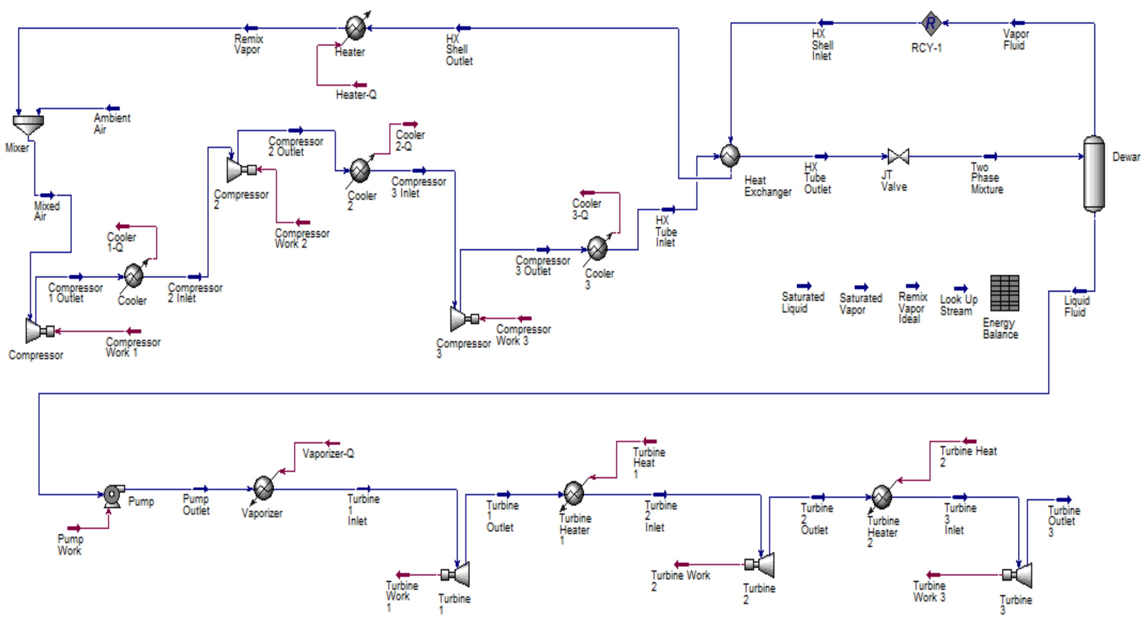

Figure 6. Validated Aspen HYSYS LAES model. Adapted from Willis (2018).

E. RESULTS AND ANALYSIS

Component operating parameters were calculated and analyzed in order to set requirements for the system. A building scale LAES system was simulated using Willis's validated Linde-Hampson cycle LAES model with varying component parameters.

1. Compressor

Compressor selection must balance overall system efficiency and liquid air yield. Compressors most easily vary in both pressure and flow rate. Pressures of 1000 to 4000 psi and flow rates of 5 to 40 cfm were varied and simulated through the LAES system. First overall system efficiency was analyzed. Figure 7 shows system efficiency as a function of compressor outlet pressure. Efficiency increases with increases in pressure, but flow rate has no effect on efficiency.

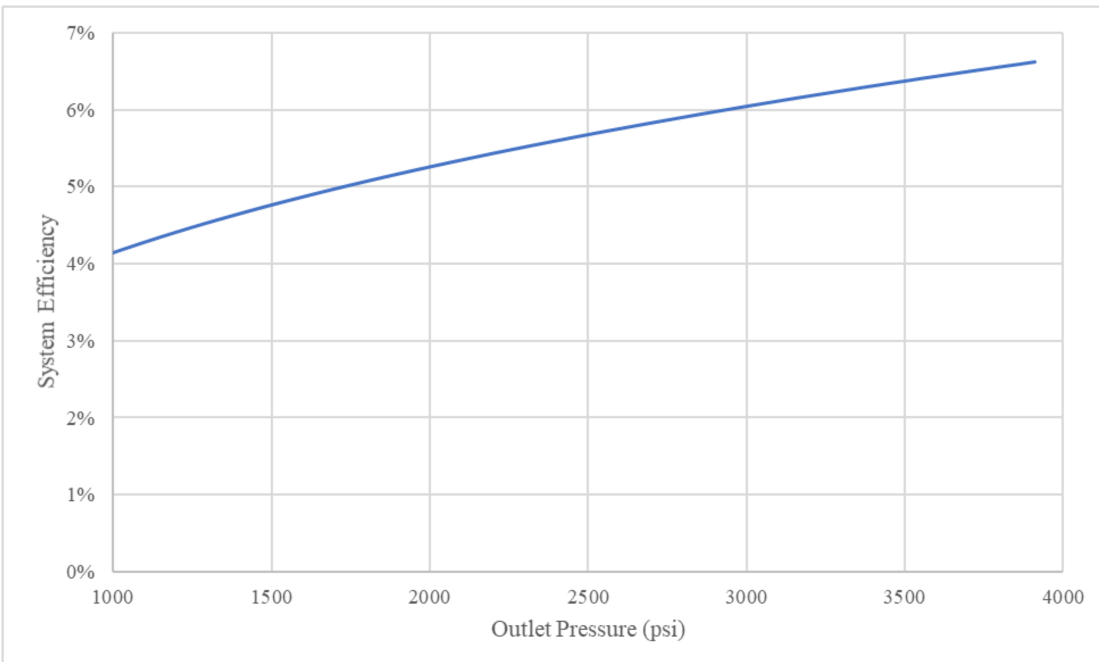

Figure 7. Theoretical LAES system efficiency over designated pressure range.

The contribution of outlet pressure and flow rate to liquid air yield was analyzed. In this case, flow rate does contribute. Figure 8 shows the liquefied air yield as a function of outlet pressure for three specific flow rates.

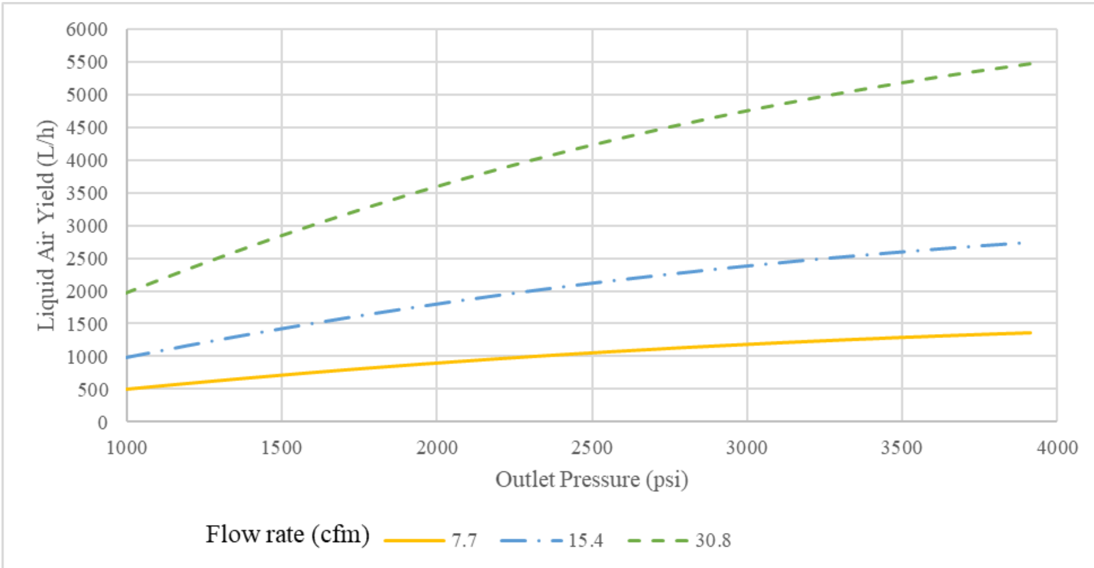

Figure 8. Liquid air yield varying pressure and flow rate.

The more important compressor parameter is flow rate. Doubling the pressure does increase the liquid yield rate by 145% but doubling the flow rate increases the liquid yield rate by 287%. Therefore, flow rate is prioritized over pressure for a LAES system compressor.

2. Heat Exchangers

Using the same range of pressures and flow rates, the cooling capacity of the heat exchangers was also examined. An increase in air moving though the system also increases necessary the cooling capacity of the heat exchanger as show in Figure 9. This varies linearly and directly with the flow rate.

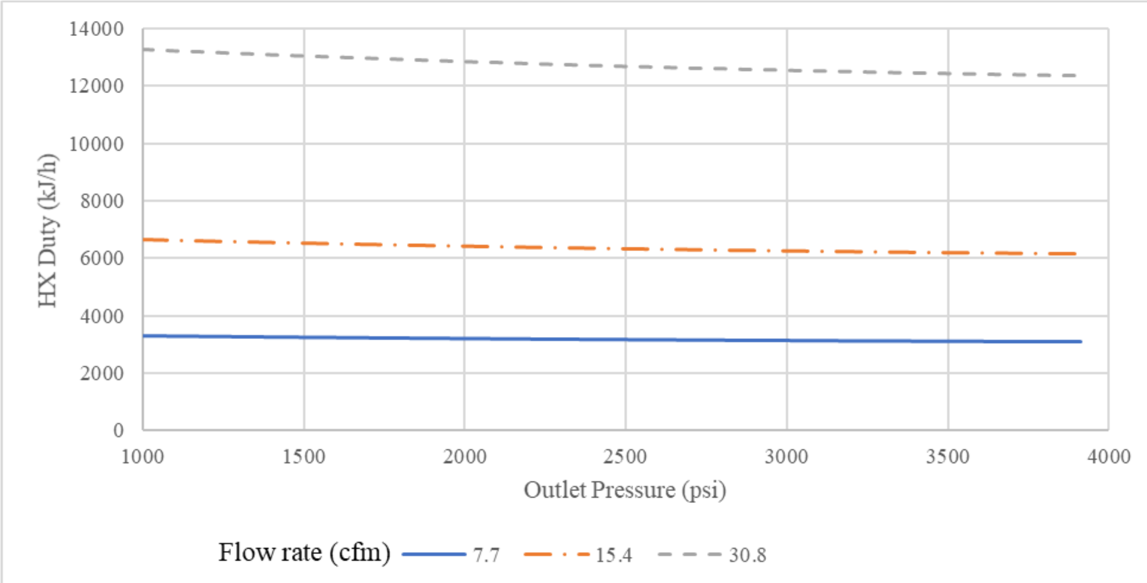

Figure 9. Heat exchanger duty varying pressure and flow rate.

The heat exchangers must also be able to withstand temperature differences of 220 °C during operation of the LAES system.

3. Dewar and Cryogenic Pump

At the five-kW frontier, the liquid air flow was constant to produce the needed power. To produce the minimum requirements, an ideal LAES system requires 52.8 L/h of liquid air to expand through the turbine generator. To operate for five hours, the system must be able to store at least 264 L of liquid air at a minimum within the dewar.

4. Turbine and Generator

Specific expansion turbine and generator requirements were not analyzed. Being at the output end of the LAES system, efficiency is the most important factor when considering these components. Any losses will have to be overcome with the generation components discussed previously.

All component requirements are summarized in Table 1.

Table 1. Summary of component requirements

Component	Requirement	Source
Compressor	≥ 1000 psi	Simulation Analysis (Howe 2018)
	≥ 5 cfm	Simulation Analysis
	Oiless	Safety Constraint
Regenerative Heat Exchanger	≥ 3800 kJ/h duty	Simulation Analysis
	≥ 220°C temperature difference	Simulation Analysis
	≥ 1000 psi	Operation Constraint
Dewar	≥ 264 L capacity	Simulation Analysis
Cryogenic Pump	≥ 52.4 L/h pump rate	Simulation Analysis
Evaporative Heat Exchanger	≥ 3800 kJ/h duty	Simulation Analysis
	≥ 220°C temperature difference	Simulation Analysis
	≥ 1000 psi	Operation Constraint
Turbine and Generator	≥ 5 kW output	Design Constraint
	High efficiency	Simulation Analysis

F. COMPONENT SELECTION AND CONFIGURATION

1. Turbine and Generator

Few of the commercially available microturbine generators operate at low enough power as to supply only five kW. Many of these systems instead are on the scale of tens to hundreds of kW. The Deprag Green Energy Turbine is one such option to satisfy the lower power demands of this system.

2. Dewar

The Cryofab 300 L horizontal LOX is an ideal dewar for the system. This dewar provides excess storage capacity as needed for the LAES system and is designed for cryogenic uses, so it is designed to handle the low temperatures associated with liquid air.

3. Cryogenic Pump

The pump to move liquid air from storage to the turbine must move 52.8 L/h to maintain five kW. This pump rate is slow for many commercially available cryopumps.

The Cryostar GBS-CBS gearbox transfer pump can pump at a low enough rate to meet system requirements.

4. Heat Exchangers

The heat exchangers chosen are manufactured by Alpha Laval. There is no specific model chosen, due to the custom nature of the component. It is a shell and tube type heat exchanger, rated for pressures of up to 4000 psi, and at greater cooling capacity than 3800 kJ/h.

5. Compressor

Table 2 compares a selection of compressors, differentiating between number of stages, operating pressures, time to recharge the system, and overall system efficiency. Efficiency and time to recharge was calculated using the same HYSYS model with the selected compressor's operating parameters.

Table 2. LAES system efficiency based upon a selection of compressors.

Compressor						Generation	Time	Energy	
Make	**Model**	**psi**	**kW**	**cfm**	**Stages**	**L/h**	**h**	**input kWh**	**Efficiency**
Artic	O3-5-A	5000	4.10135	6.5	3	1.7701	148.8193	610.36	4.10%
Artic	O3-7.5-A	5000	5.59275	9	3	2.450907	107.4806	601.1121	4.16%
Artic	O3-5-A6	6000	3.7285	5.5	3	1.561345	168.7167	629.0603	3.97%
Artic	O3-7.5-A6	6000	5.59275	8	3	2.271047	115.9927	648.7184	3.85%
Artic	E4-7.5-A6	6000	5.59275	9	4	2.554958	103.1035	576.6319	4.34%
Artic	E4-01-A6	6000	7.457	14	4	3.974379	66.2808	494.2559	5.06%
RIX	4VX Series	5000	22.371	30	4	8.169778	32.24384	721.3269	3.47%
Sundyne	LF-2000	4000	2982.8	5500	4	1379.475	0.19096	569.5965	4.39%

There is no clear standout component when compared. Most of the high-pressure compressors have lower flow rates, and therefore will take days to fully replenish the dewar with liquefied air. The described sample LAES system acts as a backup energy source when other, more reliable sources fail. These failures do not occur more than once a month on average, so the recharge time is negligible for the system. During uptimes, the LAES system will have ample time to recharge.

G. SUMMARY AND FUTURE WORK

The example system with components and requirements set previously could be a useful backup power system on a Navy installation. The footprint is small enough that it can be integrated into existing buildings and not require major renovations or rebuilding. This system would not cause a large draw on grid power with a reasonably sized compressor motor. Such a motor could also feasibly be powered from both a standard power grid and renewable energy systems alike. The LAES system requires days of continuous operation to charge the dewar with liquid air, but if operated intermittently during peak generation times, it can operate seamlessly in the background and be ready during outages. Generation periods can be spread over a month without major impact on the building's functions. When fully recharged, the system would only have to run to make up liquid lost to the atmosphere from the dewar, minimal for the month.

This research identifies the driving factors that contribute to a LAES system while also helping identify sample components and ideal uses for this scale of a system. Girouard, Pollman, and Hernandez are conducting concurrent research from a supply-based LAES perspective to map what current generation methods can supply a LAES system at the same building scale (Girouard, Pollman, and Hernandez 2019). Further research and simulation must be conducted in order to find other inefficiencies within the system. Such inefficiencies may exist within the heat exchanger, piping within between components, and the non-ideal turbine generator that a real system would inevitably have. Real life systems may have to generate three to four more times the energy as the system described above to reach the five-kilowatt requirement. A prototype LAES system is under construction at the Naval Postgraduate School to provide further experimental validation of a Aspen HYSYS LAES model that can be scaled to support producing an operational building scale demonstration system. This prototype system will test the actual performance of the system.

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III. PAPER II: "Energy Recovery for Dual-Stirling Liquid Air Energy Storage Prototype"

This chapter has been prepared in conjunction with a presentation, pending acceptance into the American Society of Mechanical Engineers (ASME) Power 2020 conference by the authors Nicholas A. Bailey, Anthony G. Pollman, and Eugene Paulo. Minor edits have been made to enhance readability and adapt publication formatting.

A. ABSTRACT

Islanded, renewably powered microgrids require energy storage or emergency generation to overcome intermittency. Batteries and fossil fuel generators have traditionally filled these roles. However, liquid air energy storage (LAES) is a promising alternative. Using power in excess of immediate demand, a LAES system can liquefy and cryogenically store ambient air. When renewable generation abates, the liquid air can be expanded through a turbine to provide power to the microgrid. This study explores energy recovery from a dual Stirling cycle LAES system. Liquid air is generated by a commercial Stirling cryocooler and stored in a vacuum dewar. A second Stirling engine utilizes the temperature difference between the liquid air and surroundings to run a small electric generator. This paper focuses on energy recovery from the cryogenic liquid air through the Stirling engine using a series of experiments. Liquid air volume as a function of time and power for varying loads were measured and used to quantify the energy recovered from the stored liquid air. Energy efficiency is calculated and recommendations for design improvements are presented. Follow-on work will include design and operation of an updated dual-Stirling LAES system. This work is part of a larger effort to determine the feasibility of different energy storage methods for small, mobile applications as well as fixed infrastructure energy storage systems.

B. INTRODUCTION

Renewable energy sources are rapidly becoming more prevalent as society creates more effective energy production methods and technology. The shift to renewable sources away from current, more traditional fossil fuel-based production comes with some challenges. Current energy generation architecture is resilient when compared to renewable source generation, meaning that they can meet near-constant demand requirements without intermittency (Sovacool 2009). Lack of resiliency forces renewable source energy generation to integrate energy storage capabilities within their grids to provide energy when those renewable sources abate. To replace current grid architecture viably, intermittency must be addressed. Energy storage and optimization are also important to the Department of Defense, as careful use of energy acts as a combat multiplier (Pollman 2013). The author previously researched and investigated a Linde-Hampson LAES system at building scale, giving component recommendations and requirements (Bailey, Pollman, and Paulo 2019).

Multiple energy storage methods exist that can fill the resiliency capability gap. The most widely used storage method currently in use is battery storage. Battery storage is a rapidly developing technology field with a mature production base and a wide range of current uses. The downsides, however, are that it shares many of the undesirable byproducts and emissions that the current fossil fuel-based production systems also create. Battery storage systems are also expensive to purchase, are made with exotic materials, and will not maintain their charge for an indefinite period of time (Luo et al. 2015). Another potential technology is pumped hydroelectric generation. This method is efficient, but geographically dependent on terrain (Semadeni 2003). According to Semadeni, the downside is shared by compressed air energy storage (CAES). CAES is less efficient than pumped hydro and is geographically dependent on a large scale due to the immense caverns needed to store compressed air (Semadeni 2003). On a smaller scale, this method can use manmade tanks, but is cost and terrain prohibitive as the system scale grows. Lastly, liquid air energy storage (LAES) combines the strengths of CAES systems and battery storage into a single system that can viably eliminate intermittency (Luo et al. 2015). This promising emerging technology has high energy density compared to CAES and is more easily stored without the unfavorable emissions, exotic materials, and limited number of cycles for the system (Luo et al. 2015).

C. BACKGROUND

LAES systems, in their simplest form, liquefy ambient air then use that liquid air to create energy. Figure 10 below is a functional flow diagram for a simple LAES system.

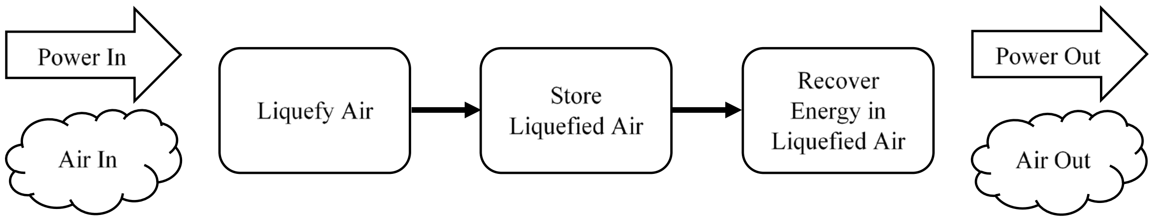

Figure 10. Functional flow diagram of a general LAES system.

Multiple methods exist for accomplishing these functions. One such system is a Linde-Hampson cycle LAES system. This method compresses the ambient air followed by rapidly isentropically expanding it, cooling it in the process (Barron 1985). When the air reaches sufficiently cold temperature to change phase, the liquid air drops into a storage dewar for later use. To generate energy in a Linde-Hampson cycle LAES system, the liquid air is heated and expanded, creating work used to drive a turbine generator (Lim, Al-Atabi, and Williams 2016). The air expands to roughly 800 times its liquid volume as a vapor (Compressed Gas Association 1999). This technology is disadvantageous in a few ways. While all LAES systems must implement cryogenic components and storage for the liquid air, the Linde-Hampson cycle also introduces high pressures associated with the liquefication function. An optimized Linde-Hampson cycle LAES system must achieve pressures of 3000–6000 psi to maximize liquid yield (Howe, Pollman, and Gannon 2018). These factors make this system harder to build and implement. Cryogenic temperatures are associated to all LAES systems inherently, but the high pressures can be eliminated by choosing a different generation and extraction method.

Originally conceived in 1816, the Stirling engine is a closed-cycle regenerative heat engine operating within the Stirling cycle. The Stirling cycle consists of reciprocating Carnot cycles and is an external combustion engine. Though multiple designs exist, the basic components of a Stirling Engine are shown in Figure 11.

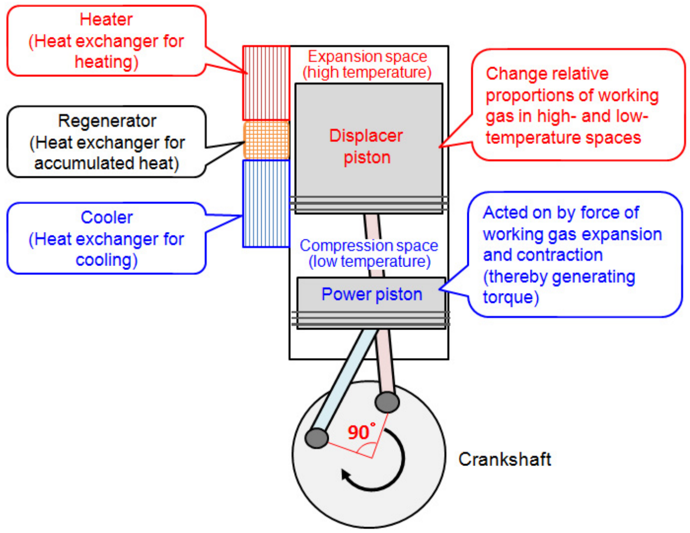

Figure 11. Beta-type Stirling engine basic components. Source: Kitazaki, Yuzaki, and Akazawa (2017).

The pressure-volume (PV) diagram for the Stirling cycle is displayed in Figure 12. The cycle consists of four distinct phases labeled a through d in Figure 12. From stage a to b, the working fluid in the cycle is isothermally compressed (Halliday, Resnick, and Walker 2014). Within this stage, heat is expelled to the sink. Next, isovolumetric heating occurs within the stage between b and c (Halliday, Resnick, and Walker 2014). The working fluid gains heat from the regenerator in this step. In the stage between c and d, the working fluid isothermally expands during which heat is absorbed from the heat source (Halliday, Resnick, and Walker 2014). Last, between d and a, the working fluid undergoes isovolumetric cooling (Halliday, Resnick, and Walker 2014). This stage transfers heat to the regenerator and cools the working fluid.

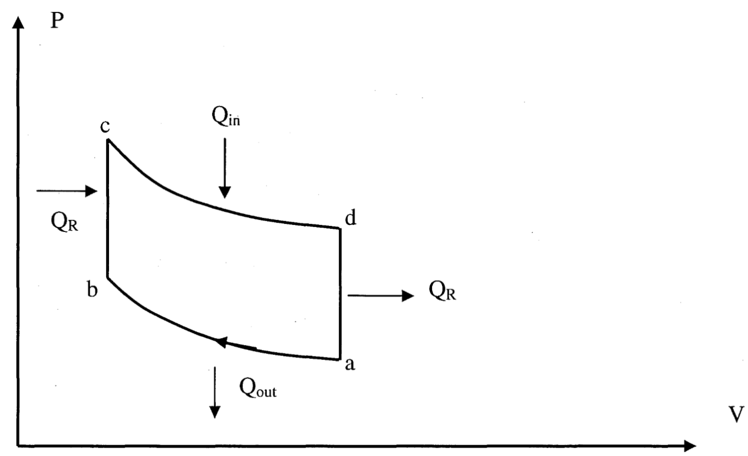

Figure 12. Stirling cycle PV diagram. Source: Shaw (2008).

The Stirling engine is traditionally used to do work through the temperature difference between a heater and cooler. However, if work is input into the system, a Stirling engine can be used to cool. (Organ 2013). This type of device is known as a Stirling cryocooler. The same concept applies toward energy extraction as well. If heat is removed from the heater component, the Stirling engine will proceed through the Stirling cycle, though it will operate in reverse. Work is output due to the temperature difference between the heater and cooler; though in this case, the heater component referred to in Figure 11 acts as the cooler and cooler acts as the heater.

An ideal Stirling engine will have efficiency based only on the difference of temperature between the heater (T_H) and cooler (T_C) (Halliday, Resnick, and Walker 2014).

$$\varepsilon = 1 - \frac{T_C}{T_H} \tag{1}$$

This represents only the ideal case, however. To more precisely estimate the efficiency of a real-world Stirling engine, more direct measurements must be made. However, Stirling remains a high efficiency cycle at the building scale (Kim, Huth, and Wood 2005).

For the dual-Stirling engine LAES system investigated in this paper, the cooler suppling T_C is supplied by the liquefied air stored within the system. As the liquid air heats, it undergoes a phase change to a vapor. The energy required to evaporate is expressed as the latent heat of vaporization. This quantity can be expressed on a per mass basis, therefore, by measuring the change in mass, the total energy required to vaporize the mass lost can be calculated. This quantity, when compared to the total energy output of the LAES system, is the actual achieved efficiency of the system.

Because the cycle is running much like a refrigerator, ideal Stirling cycle refrigeration coefficient of performance may better represent the efficiency of the cycle investigated (Halliday, Resnick, and Walker 2014).

$$COP = \frac{T_C}{T_H - T_C} \tag{2}$$

D. EXPERIMENTAL SETUP

This paper investigates the efficiency of energy recovery from liquid air. It is in conjunction with ongoing research and development into LAES systems and specifically in compliment with research into the liquid yield of the generation subsystem of this specific dual-Stirling LAES system (Girouard, Pollman, and Hernandez 2019). Though not presented, the air generation subsystem of the LAES system is produced by a Stirling cryocooler into the shared dewar with the recovery subsystem.

The complete experimental apparatus setup is presented in Figure 13. The Stirling engine chosen was a Kontax KS18 beta-type Stirling engine. It is normally used as a desktop model. One of the output flywheels of the system was coupled by a pulley to a three to twelve-volt DC electric generator, designed for use as a small hobby electrical motor. The output of the electric generator was connected to a power monitor that displays voltage and current precise to four decimal places. Connected to the output of the power monitor was the resistive load for the system. This resistive load was a variable for the experiment ranging from twenty-two to seventy-five ohms. Temperature of the heater component was taken with a thermocouple placed on the heat sink of the Stirling engine.

The input to the Stirling engine was connected to a solid copper rod to extend the cold side of the engine further into the dewar containing liquid air. The contact surfaces of these two components were butted together tightly to ensure that there was complete conductive heat transfer between them. The dewar used was a twelve-ounce Hydro Flask stainless steel vacuum insulated wide mouth thermos. The dewar was placed on a Jennings CJ-600 mass balance precise to 0.1 grams.

The overall energy efficiency and energy density of the recovery Stirling engine was determined by measuring and calculating the total energy required to vaporize the mass of liquid air consumed versus the total energy measured as an output to the system. Energy output was measured as electrical voltage and current output from a coupled electrical generator to the output of the Stirling engine. These measurements were taken at fifteen second intervals over a five-minute period. Because the output was electrical, the load resistance at which voltage and current were measured was varied to see what effect, if any, it had on output. All experimental runs were completed in triplicate to support statistical analysis.

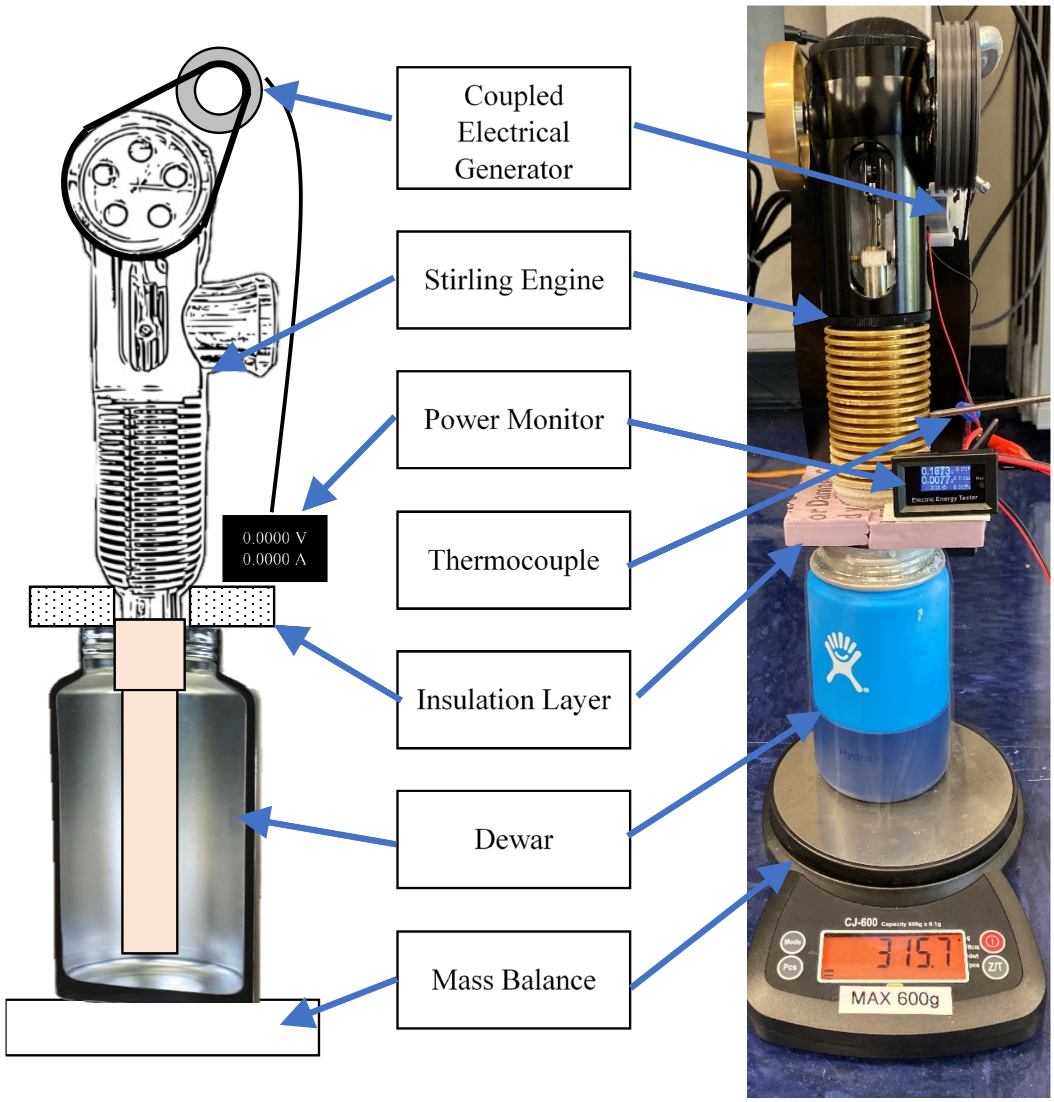

Figure 13. Experimental apparatus setup and components.

E. DATA AND ANALYSIS

First, to more accurately account for liquid air mass lost from running the Stirling engine, the loss rate of the experimental apparatus was determined. For this to occur, the apparatus was erected exactly as it would be, but the engine was not running. The change in mass due to liquid air boil off was recorded at 15 second intervals over ten minutes with the results plotted in Figure 14.

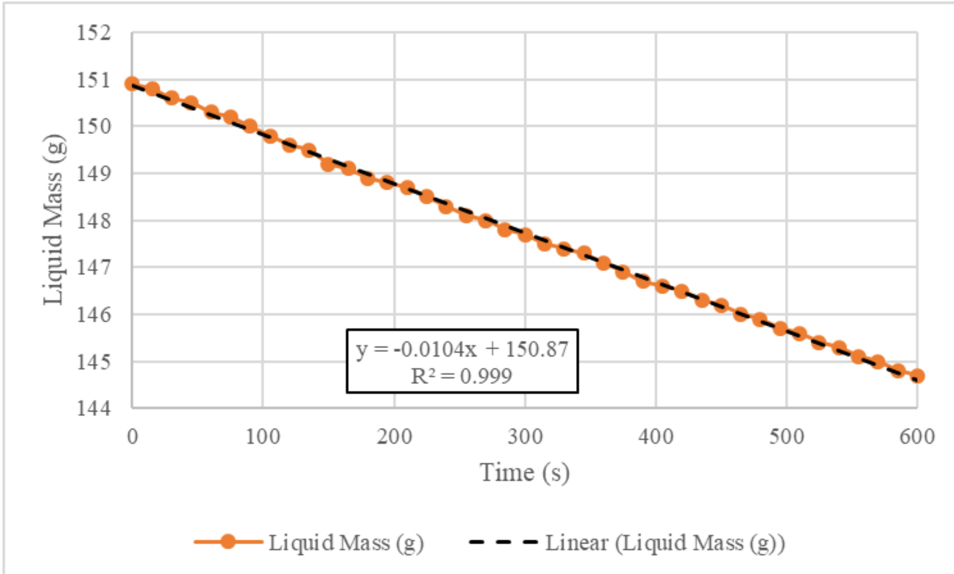

Figure 14. Evaporative loss rate of liquid air within apparatus.

The loss rate follows a linear trend and is described with the equation displayed in Figure 14. For each five-minute trial run in subsequent experiments, the apparatus is expected to lose 3.132 g or 3.881 mL of liquid air solely due to boil off.

Five different resistive loads were used during the experimental runs. These loads ranged from 22 to 75 ohms. Each experimentally loaded run was repeated three times measuring voltage, current, change in liquid air mass, and Stirling engine heat sink temperature. Power was calculated using the recorded values for voltage and current. The three experimental runs for each series were averaged and the power versus time for all tested loads is plotted in Figure 15.

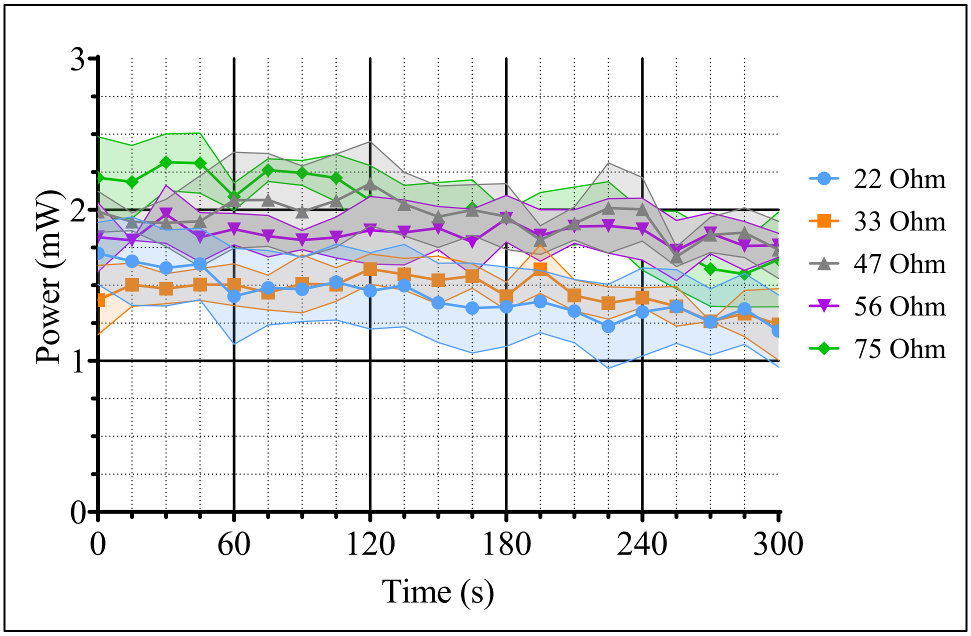

Figure 15. Power over time for varied resistive loads with standard error bands.

The standard error for each run is displayed as the error bar surrounding each averaged run. The resistive loads tested showed no significant differences in power output. The area under each curve corresponds to the total energy output of the system. Figure 16 presents the energy over time for averaged for each resistive load. The shaded bands represent the standard error of each load. As with the power over time, the energy over time appears inconclusive to change with load.

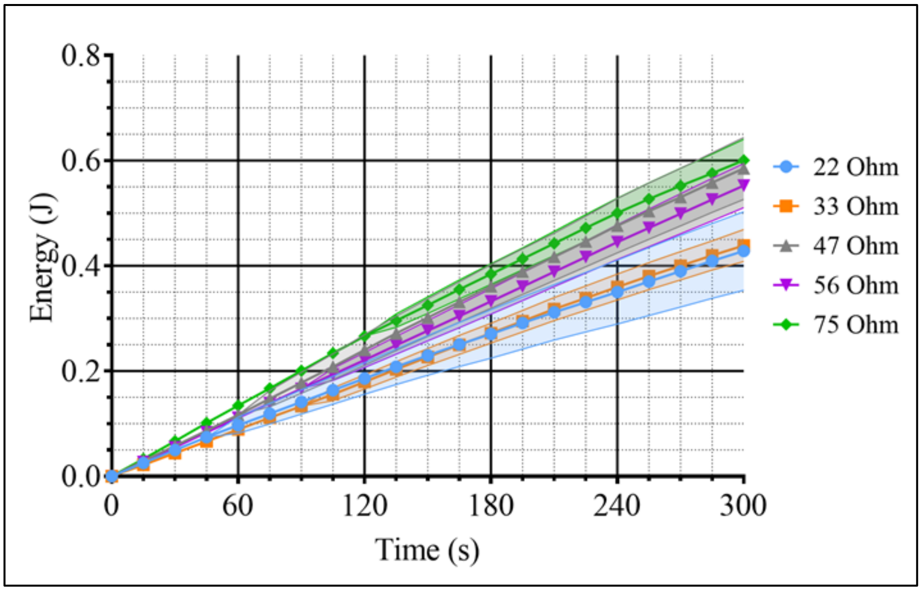

Figure 16. Energy over time for varied resistive loads with standard error bands.

Next, the mass difference and density of liquid air consumed during each run was used to calculate the volume consumed per trial run. The expected boil off volume per trial was subtracted from the total, and the total energy created per volume was calculated. This energy density is shown in Figure 17. The energy density across all loads and trials averages 32.54 J/L.

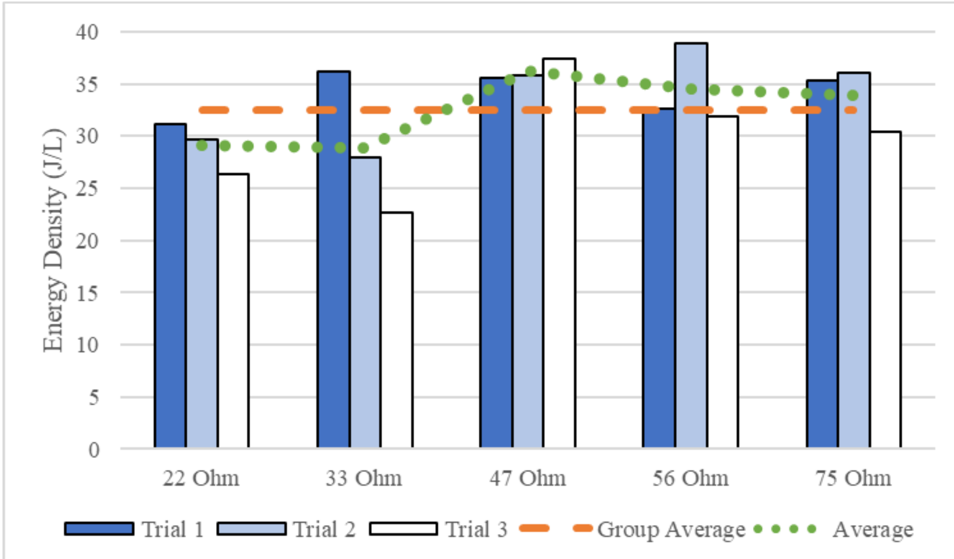

Figure 17. Energy density of experimental conditions.

Comparing this system's energy density with other LAES system energy of 255.7 kJ/L gives a system efficiency of 0.0127% (Wang et al. 2015). Another measure of efficiency comes from comparing the latent heat of vaporization for air and the achieved energy output of the system. Table 3 describes the efficiency through this method.

Table 3. Calculated system efficiency by latent heat of vaporization.

	Trial	Liquid Lost (g)	Exp. Boil Off (g)	Engine Consumed (g)	Energy Out (J)	Latent Heat (J)	Efficiency		
22 Ω	1	25.3	3.88	21.42	0.54	4262.4	0.0126%	0.0118%	0.0132%
	2	15.8		11.92	0.29	2371.9	0.0120%		
	3	25.5		21.62	0.46	4302.2	0.0107%		
33 Ω	1	20.9	3.88	17.02	0.50	3386.8	0.0147%	0.0117%	
	2	21.4		17.52	0.39	3486.3	0.0113%		
	3	27.1		23.22	0.42	4620.6	0.0092%		
47 Ω	1	22.3	3.88	18.42	0.53	3665.4	0.0144%	0.0147%	
	2	22		18.12	0.52	3605.7	0.0145%		
	3	27.2		23.32	0.70	4640.5	0.0152%		
56 Ω	1	21.8	3.88	17.92	0.47	3565.9	0.0132%	0.0140%	
	2	23.4		19.52	0.61	3884.3	0.0158%		
	3	26.1		22.22	0.57	4421.6	0.0129%		
75 Ω	1	24.5	3.88	20.62	0.59	4103.2	0.0143%	0.0138%	
	2	27.1		23.22	0.68	4620.6	0.0146%		
	3	25.8		21.92	0.54	4361.9	0.0123%		

Both methods reach similar efficiency percentages. Comparing against the ideal Stirling cycle efficiency shows the extreme amount of losses within this system and setup. Table 4 displays the average measured temperature per run (T_H), the boiling point of liquid air (T_C), and the ideal Stirling efficiencies and coefficients of performance using equations (1) and (2).

Table 4. Ideal Stirling cycle efficiencies and coefficients of performance.

	Average T_H (K)	TC (K)	Ideal Efficiency		Ideal COP	
22 Ω	275.40	77.00	72.04%	71.83%	38.81%	39.22%
33 Ω	271.82		71.67%		39.52%	
47 Ω	273.08		71.80%		39.27%	
56 Ω	272.39		71.73%		39.41%	
75 Ω	273.96		71.89%		39.09%	

The achieved system efficiency and coefficient of performance is over three orders of magnitude below the ideal. The losses within the system contribute to this large discrepancy. The largest observed loss was within the Stirling engine itself. It conducted heat from the environment into the dewar at a high rate. Also, as the Stirling engine cooled, the working mechanisms within cooled and contracted, making the engine less efficient. The engine had to be allowed to return closer to environment temperature rather than operate at extreme cold temperatures. Even as ideal Stirling efficiency dropped due to smaller temperature differences, the achieved energy output when the engine reached to these temperatures dropped faster than ideal efficiency calculations predicted.

Other sources of error observed during experimentation where the inconsistencies of temperature measurements on the heat sink of the engine. The measured sink temperature did not accurately represent the engine temperature and the temperature from one end of the sink to the other would drastically differ. The lower end of the sink would also begin to ice as moisture in the air condensed and froze during experimentation. Another source of decreased efficiency is the use of a pully driven electrical generator to provide energy. The low efficiency of the Stirling engine was coupled with low efficiency of the chosen micro-generator, compounding energy losses.

F. CONCLUSIONS

This paper explores the viability and efficiency of using a Stirling engine as an energy recovery source powered by liquefied air. The experimental setup and apparatus were not ideal, leading to a dramatic loss in efficiency within the system. By optimizing the observed loss areas identified previously, the shortfalls of this chosen LAES design can be mitigated. Furthermore, the experimentation proves that load is not a factor when designing for energy output of the system. Efficiencies measured in both energy density and using latent heat of vaporization show that the system is operating at the calculated capability.

Future design work should be into optimizing the components and minimizing thermal losses. One such improvement may be to isolate the hot end of the engine out of the environment and extend the conductive cold tip of the engine into the dewar. This will dramatically cut heat gain from the environment and keep the temperature difference high. Another improvement may be to submerge the hot end of the engine into a fluid such as water with very high latent heat values. This would serve the same function as the previous, keeping the hot temperature constant and temperature difference high. Last, a better electrical generation method can be investigated to reduce losses and take advantage of the linear reciprocation method of the beta type Stirling engine. The low torque generated forced this experiment to use micro-generators due to their low torque operation. These generators were inefficiently rated and could not provide the number of windings and number of revolutions per second to create higher power.

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IV. CONCLUSION AND FUTURE WORK

This thesis presented motivation and background for liquid air energy storage systems, conceptualization of a Linde-Hampson LAES system based on modeling and simulation, and an initial dual-Stirling engine prototype with efficiency calculations. The need for such systems comes from a changing world temperament towards renewable energy. The shift to these renewable sources will require mitigation of their inherent disadvantages. The intermittency deficiency of renewable sources can be diminished with the emerging LAES technology field. LAES systems offer high energy density, an abundant fuel supply, and do not use or create the harmful byproducts associated with other competing technologies.

Chapter II described a Linde-Hampson LAES system using a validated model to select components and offer a glimpse at how a potential system may be realized. The scale of the system was based on typical building power consumption, nominally five kilowatts. At this scale, a LAES system offers potential use as a backup power system, providing energy when the primary source abates. The system charges when the primary power source makes energy in excess of current demand, which is traditionally lost energy for such systems. Performance metrics of this sample Linde-Hampson LAES system are based primarily on the selected compressor, with pressure and flow rate being the most important factors. Further research into this type of system is underway at the Naval Postgraduate School. Currently, a prototype system is being developed to realize this system at a small-scale level.

Chapter III presented a prototype energy extraction subsystem within a dual-Stirling LAES system. Utilizing the Stirling cycle and the temperature difference between the boiling point of liquid air and the ambient environment, energy generation was proven possible. Generation efficiency was calculated using both the calculated experimental energy densities observed and by comparing latent heat of vaporization for the cryogenic fuel versus observed energy output. While the prototype proved that the technology is feasibly possible, the efficiency was extremely low due to inefficiencies within the design, components, and experimental apparatus. Future improvements to the system lie in isolating the subsystem from the environment to lessen the heat transfer from the environment and improve efficiency.

LAES systems are promising technologies to support the Navy's stated goal of reduction on fossil-fuel dependence for energy. Work presented in this thesis provides two different types of LAES systems that may help alleviate fossil-fuel dependence. Additionally, the systems presented offer a viable option towards a renewable energy shift on shore installations, though are not as suitable a fit for smaller scale applications such as microgrids to support USMC expeditionary forces. With renewable energy generation and LAES system coupled, energy resiliency is achieved through the mitigation of intermittency. The presented systems are at different stages within the systems engineering Vee, though both can contribute towards the changing energy generation field. Further research into LAES systems include the realization of a building-scale Linde-Hampson LAES system and further optimization of the dual-Stirling LAES system.

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